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GEOCHEMICAL INVESTIGATION OF HOT SPRINGS IN THE BUR NI GEUREUDONG GEOTHERMAL PROSPECT AREA, ACEH-INDONESIA

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ABSTRACT

The Bur Ni Geureudong volcanic complex is a potential area for geothermal development and utility. This volcanic complex is situated in northern Sumatra, Aceh Province, Indonesia. Geothermal potential in this area is manifested by several hot springs discharged in the Pinto Rime Gayo (PRG), Simpang Balek (SB), Uning Bertih (UB), and Silih Nara (SN) springs. All springs have a neutral pH and a surface temperature ranges from 34.10 to 67.11ºC. A geochemical investigation was conducted on the hot springs to understand the hydrochemistry of the geothermal fluid and estimate the reservoir temperature of the geothermal area. This investigation was an exploration study of geothermal resources in the area. Hot waters in the PRG, SB, UB, and SN springs were collected and analyzed in May 2018 to identify the cations and anions contained. Piper and Cl-SO_4-HCO_3 diagrams have been plotted to characterize the geothermal fluid. Na/K geothermometer has been applied to calculate the temperature of the geothermal reservoir. Isotope analysis has also been conducted to estimate the origin of the fluid. This research discovered that the major element of the water demonstrates the various geothermal water types. The PRG spring contains Na-K-Cl water, whereas the SN spring contains diluted Cl-HCO_3 water with mixed cation concentrations of Ca, Mg, Na, and K. The waters in SB and UB are a mixed form of Cl-HCO_3-SO_4 waters. According to the δD and $\delta^{18}O$ relationship, the genesis of geothermal fluids is hydrothermal fluids of meteoric water. Based on the Na/K geothermometer, the reservoir temperature of the Bur Ni Geureudong geothermal system is a range of 171-289ºC which is indicated as a high enthalpy system (>225ºC). It can be concluded the Bur Ni Geureudong geothermal region is recognized by this study as a promising source of renewable energy. Future work on geothermal exploration and utilization is expected to expand on the framework established by this present study.

Keywords: Geochemical Investigation, Geothermal Energy, Bur Ni Geureudong Vulcanic Complex, Geothermal Fluid

RASĀYAN *J. Chem.*, Vol. 16, No. 3, 2023

INTRODUCTION

Indonesia has an enormous population, making it challenging to maintain access to electricity.[1] Until 2019, Indonesia's electrification rate had reached 90%. It indicates that almost all Indonesian people have access to electricity, although they are spread across five main islands and thousands of remote islands.[2] Electricity consumption is expected to increase by 8.5% per year by 2025.[3] Fossil fuels, cannot be the primary source of electrical energy. It contributes to greenhouse gas emissions. As a result, the Indonesian government encourages environmentally friendly economic development, such as the implementation of sustainable geothermal energy to meet the country's energy demands.[4] Due to its geological setting on an active plate, subduction zone, and magmatic setting, Indonesia has the largest geothermal prospect with up to 310 prospects.[5,6] According to the Indonesian Geological Agency (2020), Indonesia has a geothermal potential of approximately 23.9 GWe, but only 8.9% of it has been utilized. Aceh Province has massive geothermal potentials, including manifestations in Seulawah Agam Jaboi, and Bur Ni Geureudong volcanoes.[7,8,9] The existence of geothermal potential in Bur Ni Geureudong is indicated by thermal manifestations of hot springs, solfataras, and fumarole implying the heat transfer is dominated by fluid flow. Since water is the primary mineral resource in the world that is essential for survival[10], hot water is currently being used directly for daily activities in the Bur Ni Geureudong area. However, the previous exploratory studies for geothermal resources are still limited to geophysical[11,12,13] and remote sensing methods.[14] No publication about the geochemical investigation has been completed. The geochemical analysis is required in geothermal exploration to understand the properties of geothermal fluids, particularly in estimating reservoir temperatures using geothermometer equations.[15] This paper describes a geochemical investigation of hot springs water distributed in the Bur Ni Geureudong Volcanic Complex. The geochemical investigations included in-situ measurements and analysis of geothermal water samples through a chemical hydro-geothermometer application, isotope analysis, and cation-anion analysis. This study aimed to examine the temperature of the geothermal reservoir beneath the Bur Ni Geureudong volcanic area as well as its hydrochemistry and genesis of the geothermal fluid.

EXPERIMENTAL

Water Sampling

A geochemical survey was carried out at six hot springs in the Bur Ni Geureudong Volcanic Complex: Pinto Rime Gayo (PRG-1 and PRG-2), Simpang Balek (SB-1 and SB-2), Uning Bertih (UB), and Silih Nara (SN) springs which is situated in the northern region of Sumatra Island, Aceh, Indonesia (Fig.-1). Most of the hot springs and solfataras in this area are associated with the geothermal system and can be found on both the northern and southern slopes. The geothermal system in the area is a volcanic-hosted play influenced by the Great Sumatra Fault zone as a result of subduction on the Eurasian and Indo-Australian plates.[16–19] Volcanic sedimentary layers predominate in this region, and several nearby local faults are found close to thermal manifestations.[20] These defects are thought to perform as porous pathways that enable fluid flow discharge to the outflow zone.[21] Physical and chemical data from PRG-1, PRG-2, SB-1, SB-2, UB, and SN springs were observed in-situ, including surface water temperature (Fisher Scientific Traceable), Total Dissolved Solids (TDS) values (Hanna), and pH and conductivity values (Schott Instrument). The overall equipment was set up in accordance with Nicholson's (1993) guidelines,[22] and a GPS device (Garmin 62S) was utilized to coordinate the marking and elevation of every sample's location. Samples of the hot water were collected from the hot springs and inserted into polyethylene (PE) bottle and filtered through filter paper (Whatman) with a pore size of 0.45 μm. The water samples were utilized to identify cations and anions as well as to examine the isotopes (δD and $\delta^{18}O$) that were contained in the water. For cation testing, water samples were acidified with 6N HNO_3 solution until the pH was below 2; for anion testing, no additions were made (non-acidified). To avoid silica deposition, SiO_2 analysis was conducted by dissolving in deionized water. A coolbox was used to transport sample bottles to the lab for analysis.

Analytical Methods

Water samples were then sent to the Laboratory of the Indonesian Industrial Research and Development Agency (BATAN) to be characterized chemically and analyzed isotopically. The analysis of cations content (K, Na, Mg, Ca, Li, B) was performed using an Argon gas burner and an Inductively Coupled Plasma-

Optical Emission Spectrometer (ICP-OES) (Thermo Scientific, iCAP 7400). Next, analysis of anions content (SO_4, F, Cl, NO_3) was performed using Ion Chromatography (Metrohm, IC Plus 883) column (Metrosep A Supp 5-150/4.0), the diluent composition of 1 mmol/L $NaHCO_3$ + 3.2 mmol/L Na_2CO_3 dissolved in aquabidestillate and acetone solution (49:1, v/v), the flow of 0.700 mL/min and pressure of 9.63 MPa. The SiO_2 ion analysis was then performed using a UV-Vis spectrophotometer (Thermo Scientific, Genesys 10S). The alkalimetric titration method was used to analyze the HCO_3 ions. Later, using Laser Spectroscopic Analysis, water isotopes (δD and $\delta^{18}O$) were investigated (LGR DT-100 Liquid Water Stable Isotope Analyzer). The isotope ratio values were compared to the international standard Vienna Standard Mean Ocean Water (VSMOW) chart, which has an analytical precision of less than 0.6 for δD and 0.1 for $\delta^{18}O$. The uncertainty measurement of the anion and cation concentrations was calculated using the standard deviation of the concentration with the LINEST method to obtain several statistical data functions.[23-24]

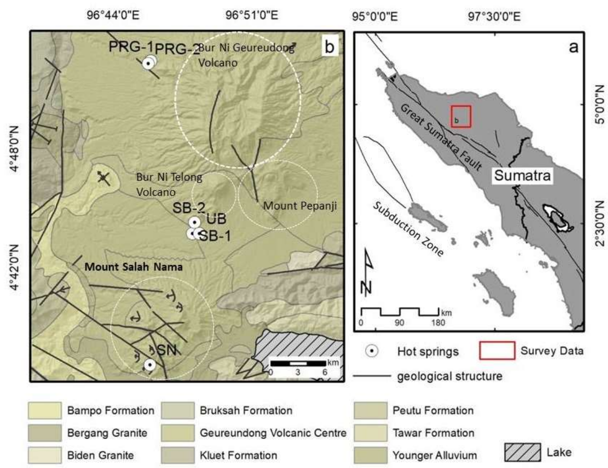

Fig.-1: Geological Setting of Bur Ni Geureudong Volcanic Area and the Location of Thermal Water Sampling in Circles Black Dot (Modified From[20])

Hydro-Geothermometry

The hydro-geothermometry was performed based on the value of the content of cations and anions. Na-K-Mg ternary diagram and Na/K geothermometer were used in this calculation. The Na-K-Mg ternary diagram was used to detect water-rock equilibrium and calculate reservoir temperature. The Na/K geothermometer was commonly used in high-temperature systems above 150°C, which was estimated as appropriate for the Bur Ni Geureudong geothermal prospect area.[22] To obtain a more accurate reservoir temperature, six Na-K geothermometer equations[25-30] were applied to water samples from PRG-1, PRG-2, SB-1, SB-2, UB, and SN (Table-1).

Table-1: List of Na-K Geothermometer Equations (°C)

Equations	References
$T = [855.6 / (0.857 + \log(Na/K))] - 273.15$	28
$T = [833.0 / (0.780 + \log(Na/K))] - 273.15$	27
$T = [1,319.0 / (1.699 + \log(Na/K))] - 273.15$	30
$T = [1,217.0 / (1.483 + \log(Na/K))] - 273.15$	26
$T = [1,178.0 / (1.470 + \log(Na/K))] - 273.15$	29
$T = [1,390.0 / (1.750 + \log(Na/K))] - 273.15$	25

RESULTS AND DISCUSSION

Hydrothermal Characteristics and Chemical Composition

The results of on-site water physical and chemical investigation in the PRG-1, PRG-2, SB-1, SB-2, UB, and SN springs were presented in Table-2. The surface temperature of the waters ranged from 34.10 to 67.11°C, with PRG-1 having the highest temperature and SN having the lowest. TDS values between 0.76 to 21.4 (g/L), and EC values between 1.54 to 42.3 (mS/cm), while pH in all of the springs is nearly constant at 5.56 to 6.18, indicating neutral acidity. The hot springs are situated in various elevations. The PRG-1 and PRG-2 springs are located at a lower elevation of 988 meters asl, while other hot springs are located at elevations of more than 1200 meters asl. The PRG-1, PRG-2, and SN waters are slightly murky and brownish, whereas the SB-1, SB-2, and UB waters are very clear. PRG-1, UB, and SN hot water ascend and mix with cold water at the river's bottom. The conductivity and water temperature are associated with the rock-water reaction.

Table-2: Characteristics of Water Discharged in the Bur Ni Geureudong Hot Springs

Location	Point	Coordinates (°)		Elevation (masl)	T_{water} (°C)	pH	EC (mS)	TDS (g/L)
		Latitude	Longitude					
Pinto Rime Gayo	PRG-1	4.8730	96.7650	988	67.11±0.14	5.86±0.01	42.3±0.21	21.4±0.19
	PRG-2	4.8709	96.7630	988	61.04±0.01	5.96±0.01	28.6±0.13	14.5±0.11
Simpang Balik	SB-1	4.7280	96.8000	1217	49.71±0.01	5.92±0.01	3.79±0.13	1.79±0.04
	SB-2	4.7372	96.8018	1258	43.76±0.03	6.18±0.05	2.41±0.06	1.30±0.01
Uning Bertih	UB	4.7279	96.8059	1252	45.46±0.06	6.02±0.01	3.37±0.05	1.84±0.09
Silih Nara	SN	4.6174	96.7644	1431	34.10±0.01	5.56±0.01	1.54±0.01	0.76±0.01

Table-3 and Table-4 demonstrate the hydro-chemistry of cation and anion concentrations contained in the thermal water of the hot springs, respectively. The ion concentration was also calculated the uncertainty value using the Standard Deviation of Concentration (SC) proposed by Skoog.[23-24] Compared to other springs, PRG-1 and PRG-2 have a higher chloride content. The concentration of chloride and other dissolved substances changes as fluid flows to the surface from the reservoir. Silica content (SiO_2) of the hot springs varies from 19.4 to 33.7 mg/kg. SN springs have the highest silica. During the process of deposition over a geologic time scale, the silica was transported away. When fluid and rock interact at high temperatures, geothermal fluids may include a lot of silica.[32,33] The data of cation and anion concentrations were used to calculate temperature of reservoir, explaining the chemical equilibrium of water and the characteristics of geothermal water types. The anion-cation composition of geochemical elements expressed in the Piper diagram which identifies three types of fluid: cation-chloride water, cation-bicarbonate water, and cation-sulfate water.[34] The diagram shown in Figure-2a discribed that the PRG-1, PRG-2, and SB-1 waters are dominated by Sodium (Na) and Potassium (K) as the cation and Chloride (Cl) as the anion (Na-K-Cl), while the SB-2, UB and SN waters do not present a dominant cation and anion type. It suggests the waters in SB2, UB and SN springs are a mixture type of water. To find out the type of water based on anions concentration more accurately in PRG-1, PRG-2, SB-1, SB-2, UB and SN springs, an analysis was carried out through the Cl-SO_4-HCO_3 ternary diagram (Fig.-2b).

Table-3: Anion and Isotopic Content in Geothermal Water of the Bur Ni Geureudong Rrea (mg/kg)

Code	HCO_3	Cl	SO_4	F	δD (‰)	$\delta^{18}O$ (‰)
PRG-1	532.09±5.12	10,388.89±1.42	20.16±0.87	0.21±0.11	-67.6±2.2	-8.86±1.25
PRG-2	585.93±4.32	10,445.19±1.43	22.27±0.90	-	-66.3±2.6	-7.16±0.39
SB-1	1,069.35±8.63	1,191.62±0.50	767.99±0.62	0.17±0.11	-65.9±0.7	-9.98±0.38
SB-2	561.49± 3.32	449.87±0.32	546.81±0.57	0.20±0.11	-64.0±3.1	-9.13±0.58
UB	789.78±5.18	688.52±0.39	514.43±0.56	0.25±0.11	-64.7±1.7	-8.71±0.32
SN	578.43±4.92	298.17±0.50	34.30±1.08	0.37±0.11	-65.4±1.4	-9.96±0.28

Table-4: Cation content in geothermal water of the Bur Ni Geureudong area (mg/kg)

Code	Na	Mg	K	Ca	Li	B	SiO_2
PRG-1	915.34±1.12	20.33±1.21	88.45±0.64	132.19±1.25	0.45±0.37	10.5±0.05	19.4±1.33
PRG-2	1564.49±1.08	59.19±1.29	133.50±0.55	391.23±1.25	6.98±0.39	12.0±0.03	31.1±1.55
SB-1	1247.46±1.07	10.96±1.19	168.21±0.57	296.80±1.24	3.76±0.38	0.92±0.01	20.0±2.11

SB-2	45.76±1.14	29.97±1.23	7.40±0.77	67.79±1.51	-	0.68±0.02	22.9±2.12
UB	102.15±1.24	71.17±1.32	15.40±0.99	72.60±1.53	-	1.05±0.01	22.4±1.93
SN	176.40±1.06	44.88±1.26	24.70±0.54	190.46±1.26	0.15±0.37	0.52±0.01	33.7±3.53

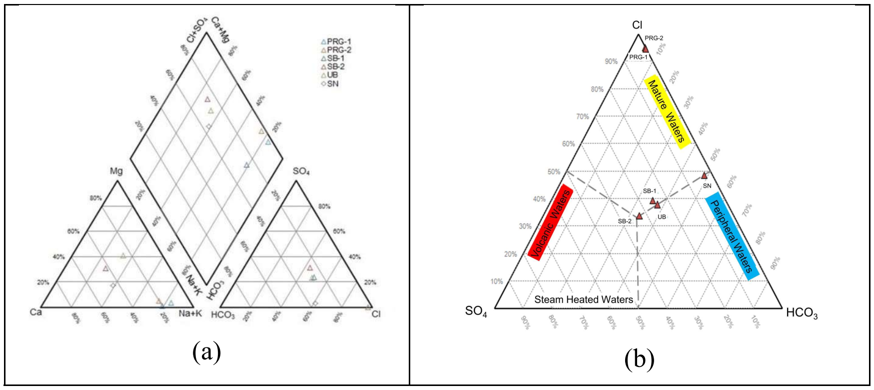

Fig.-2: (a) Piper Diagram (b) Ternary Diagram of Cl-SO4- of the Bur Ni Geureudong Thermal Springs Water

Based on the predominate anion content, geothermal water could be categorized using the Cl-SO_4-HCO_3 ternary diagrams. The presence of three types of water is indicated by anion-based classification of geothermal water. Specifically, chloride, sulfate, and bicarbonate. According to the ternary diagram, the waters in PRG-1 and PRG-2 are chloride water and thus mature water. While the waters in SB-1, SB-2, and UB are mixed Cl-SO_4-HCO_3 water, and the water in SN spring is classified as diluted Cl-HCO_3 water. Majumdar (2009) reported a similar case at Bakreshwar spring in Eastern India, where several geothermal springs experience mixing between Cl-SO_4-HCO_3 anions originating from groundwater and hot springs.[35] The mixing anions is estimated as a result of surface water-rock interaction, such as hot springs in the Ungaran geothermal field.[36] The Na-K-Mg ternary diagram explaine geothermal fluid water-rock equilibrium and estimated reservoir temperature based on cation composition. According to the Na-K-Mg ternary plot (Fig.-3), SB-1 is the only partially equilibrated water. It indicates the presence of aquifer dilution or mixing of hot and cold groundwater. The ionic equilibrium between water and rock has not been fully reached, and dissolution remains continuous.[37] Major anion ternary plot, which represented the dilution of Cl-HCO_3-SO_4 water in SB-1, confirmed this (Fig.-2b). Because SB-1 is known to be in partial equilibrium in the Na-K-Mg diagram, the reservoir temperature can be predicted directly using this diagram, which is between 240-260°C. On the other hand, the major cation plot reveals that PRG-1, PRG-2, SB-2, UB, and SN are immature waters that have not reached the water-rock equilibrium. As a result, reservoir temperature estimation using Na-K-Mg geothermometer is inappropriate for this system. Points near the Mg root corner indicated that the water system contained a high proportion of relatively mixed cold groundwater.[36] The mixing of Cl-water from deep reservoir fluid with Mg^+-rich groundwater (river) confirms the immature waters in PRG-1 and PRG-2. Several geothermometers have been proposed, but not all geothermometers are appropriate for all springs. It's due to the complexity of geothermal systems, and many subsurface processes can cause variations in geothermometer results. Lateral flow may exist, which is influenced by the high-relief topography and a low permeability horizontal rock near the surface, resulting in the mixture of geothermal water. This situation is typical of a high-temperature liquid dominated system in an andesitic volcano with a high topography of more than 1000m. It occurs close to the edges of the main up-flow and outflow zones in high temperature systems. It generally has warm-temperature springs that are elevated higher than chloride-water springs.[39]

Thermal Reservoir Temperature

The reservoir temperature of PRG-1, PRG-2, SB-1, SB-2, UB, and SN springs was calculated using the Na/K geothermometer. In common geochemical processes such as geothermal fluid mixing with surface waters and degassing during ascent to the surface, the geothermometer Na/K has little effect. It is preferable to use two or more Na/K geothermometer equations to obtain a comprehensive view of the temperature range.[40] The results showed all Na/K geothermometer equations had estimated reservoir temperatures in thermal springs of RPG-1, RPG-2, SB-1, SB-2, UB, and SN whose values do not exceed 350°C that are largely similar (Table-5). Reservoir temperatures for the PRG-1 and PRG-2 are 184–230°C and 171–220°C, respectively. While the UB and SN are, respectively, 236-278°C and 227-267°C, the SB-1 and SB-2 are, respectively, 222-262°C and 246-289°C.

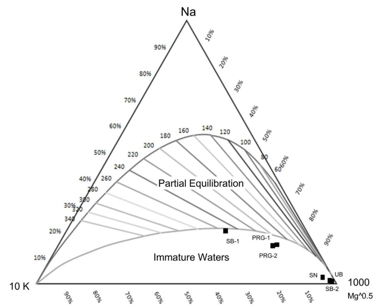

Fig.-3: Ternary Diagram of Na-K-Mg of the Bur Ni Geureudong Thermal Springs Water

The highest resevoir temperature occurs in the Simpang Balek (SB) spring. This reservoir temperature value is different from the results of surface water temperature in springs. In springs, the highest surface water temperature occurs in Pinto Rime Gayo (PGR) springs. It occurs because a fluid that rises slowly to the surface may have enough time to conductively lose heat to the cooler host rocks.[31] The results of the Na-K-Mg geothermometer and the Na-K geothermometer have similar temperatures when taking into account the partial equilibrium state at SB-1. It demonstrates that the temperatures produced by the temperature calculation are convincing ones. The temperature of reservoir of the Bur Ni Geureudong geothermal prospect area is inferred to range from 171-289°C with temperature of 233.5°C on average, implying a high-temperature system (>225°C).

Table-5: Estimated Reservoir Temperature of the Bur Ni Geureudong Thermal Waters

Code	Na/K Fournier (1979) (°C)	Na/K Truesdell (1976) (°C)	Na/K Giggenbach (1988) (°C)	Na/K Tonani (1980) (°C)	Na/K Nieva & Nieva (1987) (°C)	Na/K Arnorsson (1983) (°C)
PRG-1	214	184	230	219	201	191
PRG-2	204	171	220	204	191	179
SB-1	244	222	257	262	230	227
SB-2	262	246	274	289	248	250
UB	255	236	267	278	241	241
SN	247	227	261	267	234	232

Oxygen and Deuterium Isotope Analysis

The thermal water isotope values for oxygen (^{18}O) and deuterium (^{2}H) of PGR-1, PRG-2, SB-1, SB-2, UB and SN springs were displayed in Table-4. The relationship between $\delta^{18}O$ and δD was plotted on the V-SMOW international standard line which explained the origin of geothermal water (meteoric or magmatic water, or a mixture of both) (Fig.-4).

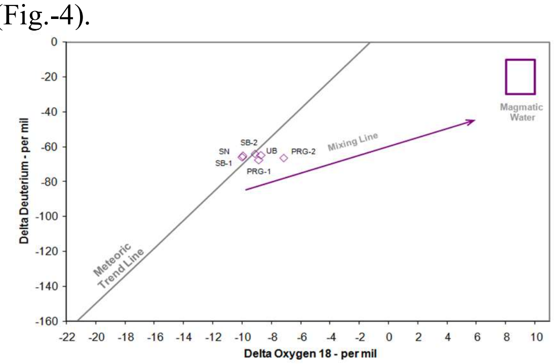

Fig.-4: A relationship Between the 18O and the D of the Thermal Waters of the PRG1, PRG2, SB1, SB2, UB, and SN Springs

The graph concluded that all of the waters are origin from meteoric water which was revealed by the cluster plotted on the LMWL line (local meteoric water line). The cluster plotted on the LMWL line indicated that all of the waters are derived from meteoric water.

CONCLUSION

The increase in the population of Indonesia causes high electricity consumption and it is estimated that Indonesia will face an electricity crisis in the future. Geochemical investigation of hot springs in the Geureudong geothermal prospect area, Aceh - Indonesia, is one attempt at the development and exploration of new renewable energy sources. Geochemistry and isotope data were carried out at six locations of thermal springs with codes PRG-1, PRG-2, SB-1, SB-2, UB, and SN. The calculations of Na/K geothermometers showed the geothermal system in the region is a high-temperature system with deep reservoir temperatures reaching 171-289ºC. Hydrochemical analysis showed the types of geothermal water and the dominant chemical contents of the thermal waters: the PRG-1 and PRG-2 springs are chloride waters with high Na+ and K+ cations, and the SN spring is dilute $Cl-HCO_3$ water with the cation concentration Ca, Mg, Na, and K are mixed. While the SB-1, SB-2, and UB springs are mixed water from $Cl-HCO_3-SO_4$ anions with concentrations of Ca, Mg, Na, and K are also mixed. The water in the SB-1 spring is in partial equilibrium and other springs are immature waters indicating the high Mg+ content due to mixing proses with groundwaters. According to isotope analysis of δD and $\delta^{18}O$, the waters from all thermal systems are thought to be derived from meteoric water that penetrated the surface to specific depths by faults or permeable ground. With a high enthalpy reservoir (>225ºC), the geochemical characteristics found in the Bur Ni Geureudong region offer a promising source of geothermal energy. As a result, the current investigation is intended to provide a basis for future work on geothermal exploration and utilization.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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[RJC- 8430/2023]